

Cognitive Control Towards Auditory Stimuli

Exam No. B076612

Word Count: 4519

Msc. Psychological Research

The University of Edinburgh

2017

ABSTRACT

Past research has found that fully developed humans show proactive cognitive control towards visual stimuli, being able to anticipate future stimuli and prepare accordingly. Our project sought to determine if this same theory applies to auditory stimuli. Using the AX-Continuous Performance Task, we had adult participants listen to different patterns of sounds and respond in one of two ways depending on the particular pair of sounds that they heard. While the experiment was taking place, we also tracked each participant's pupil dilation as a way to measure changes in mental effort. Similar to the results found in previous studies for visual stimuli, participants were slower to respond when the first sound misled them to prepare the wrong response. Most mental effort occurred during the delay between the two sounds, suggesting proactive preparation of a response. Sound type and the ratio of certain patterns occurring more than others did not affect either reaction time or pupil dilation. We found that fully developed adults show similar cognitive control towards auditory stimuli as they do towards visual stimuli. These results should encourage more cognitive control research to be based around sound, as it can be experimentally manipulated in ways that visuals cannot.

INTRODUCTION

Humans show a strong propensity for cognitive control, the ability to proactively anticipate and prepare for future events and plans. This has been demonstrated through behaviours such as inhibiting thoughts and responses irrelevant to the task at hand (Kirkham et al, 2003), and biasing towards thoughts and responses pertinent to the current task (Kane & Engle, 2003). However, it may be that individuals do not acquire these cognitive abilities until later on in life. Previous research has found evidence that argues that children lack these behaviours (Stedron et al, 2005; Zelazo et al, 2003). fMRI data seems to support these findings, showing that the children do not utilize the same regions of the prefrontal cortex used by adults during cognitive tasks (Bunge et al, 2002). These findings suggest that cognitive control is not fixed from birth, but develops and improves over time (Zelazo et al, 2003).

AX-Continuous Performance Task

Cognitive control is often divided into two types: proactive and reactive (Biggin et al, 2015). Proactive control occurs when a participant plans a response to future stimuli based on clues provided by past stimuli. In contrast, reactive control would be to respond only after being exposed to both stimuli. Experiments utilizing performance-contingent rewards have been shown to enhance the effect of proactive control (Chiew & Braver, 2013). This means that if the participants are motivated to consistently perform well, they will invest more cognitive effort during the task. This effect has been shown to be particularly influential in the AX-Continuous Performance Task (AX-CPT). In this task, the participant would see one of two possible stimuli appear on screen (A or B); this first stimulus is the “cue”. After a brief delay period, a second “probe” stimulus would appear (X or Y), after which the participant would provide a response depending on the pair of stimuli he or she had seen. AX was presented as the “target” pair and indicated its own response; AY, BX, and BY were considered “non-target” pairs and all shared a different response. In theory, AY trials should result in longer reaction times than the other types of trials, as the participant must mentally prepare for a target response after hearing the A cue and subsequently correct that preparation after hearing the Y probe.

Pupillometry

Chatham, Frank and Munakata (2009) used a variation of the AX-CPT to compare the cognitive control abilities of 3.5 year olds to those of 8 year olds (Cohen et al, 1999). They sought to figure out roughly when the development of cognitive control begins to occur and what measurable differences it makes in the child’s cognitive processing of visual stimuli. While this task was taking place, the researchers also tracked each child’s pupil dilation using an eye tracker. Evidence has been found that argues that pupil dilation indicates changes in mental effort during cognitive tasks (Kahneman, 1973; Karatekin et al, 2007). This reaction to stimuli has been found to occur in both adults and children. In this particular study, changes in pupil diameter were used to tell at what time periods during each trial the participants were thinking about how to respond. Depending on when pupil dilation occurred, the researchers would be able to discern whether each child was employing “proactive” or “reactive” control. More effort between the cue and probe suggests proactive control because it shows preparation for a possible target response. More effort after the probe suggests reactive control because it shows that they are only contemplating the correct response after both sounds have occurred.

Ratio of Trials

Chatham et al. also made sure to split the trials during each block so that 70% were target trials and 30% were non-target trials (optimally divided between AY, BX, and BY). Past studies have shown that this ratio accentuates the proactive responses, increasing mental effort during the delay period and causing more “false alarms” and worse performance on AY trials where the participant anticipates a target response (Cohen et al, 1999). Reversing this ratio (70% non-target and 30% target) seems to cause the opposite effect, leading to more reactive responses and greater mental effort occurring after the probe (Braver et al, 2001). This division of trial types allows the researchers to examine the effects of cognitive control not only through target trials, but through non-target trials as well.

Chatham, Frank, and Munakata’s results supported the idea that cognitive control develops over time. The 3.5 year olds showed greater mental effort after the second stimuli with similar reaction times between both target and non-target trials, while 8 year olds showed more mental effort between the two stimuli and reacted slower to AY trials than AX, BX, or BY trials. The researchers referred to the 3.5 year olds’ undeveloped response as reactive and the 8 year olds’ as proactive. Showing greater mental effort between the two stimuli implies that more developed children are able to plan ahead for upcoming actions based on what the first image was. This result provides useful information as to how attention develops towards visual stimuli as a person ages. However, it does not tell us whether the same rules apply to different types of stimuli.

There has been little research done on if this theory applies to the other senses, and on the direct relationships between audition and cognitive control in general. Many studies instead focus on auditory stimuli as merely a possible distraction when attending to visual stimuli (Bell et al, 2017; Hughes et al, 2012). Others have measured its effects on working memory (Sabri et al, 2014), or on how musicians compare to non-musicians in different aspects of cognition (Pallesen et al, 2010). This lack of research has left questions as to whether audition operates under all of the same cognitive mechanisms as the other senses, and if it responds in the same way to stimuli. One working memory study found that, similar to vision, audition follows the load theory of attention, where a higher perceptual load of sounds reduces perception of irrelevant sounds (Sabri et al, 2014). Another study suggested that cognitive control is domain-general in that it is utilized in all forms of cognitive conflict, from complex language to perceptual ambiguity (Kan et al, 2013). However, neither of these

studies shows that, if placed under the same conditions and task requirements to test cognitive control, audition and vision will produce similar results.

Current Study

We seek to determine if cognitive control works similarly towards auditory stimuli as it does towards visual stimuli. By using the same AX-CPT experiment structure but replacing the visual images with sounds, we can compare our results with those found from the 8 year olds. We predict that developed cognitive control mechanisms will produce similar results between both visual and auditory stimuli. We will have different participants face different types of sounds; in this case, non-verbal animal noises and spoken letter names. We predict that the type of sound will not significantly alter results in terms of cognitive control, but include this manipulation in order to account for recognizable language and sound differences as confounding factors. Finally, we will have each participant go through the experiment with two different ratios of trials (30% target and 70% non-target, or 70% target and 30% non-target). We predict that, just like with visual stimuli, adjusting the ratio of trials (having more target trials than non-target trials and vice versa) will affect the results, with more target trials making participants more proactive and more non-target trials making them more reactive.

If our hypotheses prove correct, our research will support the idea that cognitive control is domain-general and responds similarly to both aural and visual stimuli. It will also provide evidence that proactive control in adults, at least towards auditory and visual stimuli, can be suppressed and made more reactive if the participant has adapted to consistent reactive-inducing stimuli. Our research will provide another platform from which future auditory cognitive control experiments can build from. It will allow for future testing of visual stimuli as a possible distraction to aural cognition, rather than the other way around. It will make measuring pupil dilation in cognitive experiments easier and more reliable; Aspects of visual stimuli that are unrelated to mental effort, like light, can still affect pupil dilation. Aural stimuli do not cause this problem, and so would allow for more accurate measurements in a broader range of experiments. Maybe most importantly, it will provide an alternative method for examining cognitive control in individuals who suffer from poor or damaged vision.

METHODS

Participants

This experiment involved 40 normal, able-bodied participants. All participants were between the ages of 19 and 46 years ($M = 24.53$, $SD = 4.77$). There were 15 male and 25 female participants. All participants received £7 compensation for their time.

Apparatus and stimuli

All testing took place in the psychology department at the University of Edinburgh in Edinburgh, Scotland. The eye tracker used was an SR Eyelink 1000. The experiment was controlled and structured through the OpenSesame experiment building program (Mathôt et al, 2012). All animal sound files used as stimuli are public domain and were found on Freesound.org (Akkermans et al, 2011). Using the audacity sound editor (Team, 2007), sound duration was standardized at approximately 500ms each and volume was set at 50%. The spoken letter names were produced using the Mac OS X text-to-speech program. The British female voice “Kate” was used to closely match the most common accent found in the testing region. The sound file used to alert incorrect responses or timeouts was taken from an OpenSesame tutorial. All data transformations and analyses were performed on DataViewer (Fast, 2016) and in the R lme4 package (Bates et al, 2014).

Procedure

Participants’ attention and cognitive control towards auditory stimuli were tested using the AX-Continuous Performance Task (AX-CPT). This task involves listening to a cue sound (A/B) and a probe sound (X/Y), asking the participant to respond depending on the pattern of sounds that he or she heard (AX, AY, BX, or BY). There were two different versions of the AX-CPT trials used in this experiment. One condition consisted of animal sounds; A and B were a cat’s “meow” and a dog’s “bark”, while X and Y were a cow’s “moo” and a cricket’s “chirp”, respectively. The other condition consisted of a female voice speaking the actual letter names. Both types of conditions were then divided again into differing proportions of AX sounds; one version had 70% AX (target) trials and 30% AX/BX/BY (non-target) trials, while the other had 30% target and 70% non-target. Before

each trial begins, a screen appears to alert the participant that the trial is starting. All cue and probe sounds last approximately 1000 milliseconds, with a 1200ms delay in between. After the start of each probe sound, the participant has 2000ms to input a response. Target trials required a keypress of 'z', while non-target trials required a keypress of 'm'. If the response is incorrect, a corresponding sound alerts the participant to the error. The alert will also sound if the participant fails to respond during the time limit. After each trial ends and any necessary alerts are heard, the next trial begins automatically (Fig. 1). Figure 1 shows a simplified outline of the trial process.

At the start of a session, each participant read an information sheet and signed a consent form. After completing the consent form, they were then positioned into the eye tracker and had their right eye calibrated. Once the experiment began, they read the instructions on-screen and completed 8 trials of practice. After completing the practice trials, they were presented with a screen reminding them of the instructions. Each participant then faced two blocks of testing, consisting of 100 trials each. One block consisted of trials where 70% are target patterns and 30% are non-target patterns (10% for each). The second block consisted of trials where 30% are target trials and 70% are non-target trials (3/7 AX, 2/7 BX and BY). Each stimuli group was also counterbalanced so that half of its participants started with the 70%/30% block, while the other half started with the 30%/70% block. For all conditions, there was a 5-minute rest period between blocks, as well as recalibration into the eye tracker before starting the second block.

Analyses

Reaction time was measured in standard milliseconds from the time the probe sound began to whenever a response was provided. All incorrect responses and their reaction times were removed. The remaining reaction times were standardized using the log transformation function in R (Team, 2000). The data of all participants who scored below 2.5 standard deviations from the mean were removed.

To avoid variation in peak mental effort and dilation duration within both individual trial and group analysis from hiding possible effects, we tracked average percent change of pupil dilation in comparison to each subject's grand mean.

Data analysis was based around a series of linear mixed models. Our main hypothesis states that, similar to the response found towards visual stimuli (Chatham et al, 2009), participants will show varying reaction times and change in pupil dilation during non-target trials (AY, BX, BY) when compared to target trials (AX). Subjects should respond proactively during the target trials, as represented by slower reaction times and greater pupil dilation during the delay between the cue and probe. In contrast, they should respond reactively to non-target trials, with faster reaction times and greater pupil dilation when the probe sound occurs. We also predict that varying the ratio of target trials to non-target trials in a single block will affect reaction time at a rate greater than chance (50%). We believe that having a lower ratio (30%) of target trials will make the participant more reactive due to the greater abundance of non-target trials. This should force them to override their prepared response when a target trial does occur, resulting in slower reaction times. Finally, we predict that there will be no significant difference between the results for the different types of auditory stimuli (letter names, animal sounds).

RESULTS

Data trimming

We removed 4 participants with accuracy scores of <.5, <.5, .84, and .8, respectively, as they all fell outside of 2.5 standard deviations from the mean ($sd=0.042$, $mean=0.96$). By using this measure as the minimum accuracy score (.86), we were able to make sure all included participants were well above .7, the highest score achievable through perseveration of the target response. All trials that reached the 2000ms time limit or were responded to in 200ms or less were also removed, as this means that either no response was provided or the response was too fast to provide reliable data. After checking for differences in accuracy, incorrect responses that were given within the time constraints were also removed from the examined data. Reaction times from correct trials were transformed using the log transformation function in the R program (Team, 2000). This transformation is important as it standardizes the data and accounts for individual differences in processing speed (Chatham et al, 2009; Paxton et al, 2007).

All eye-tracking measurements were performed on each participant's right eye. An additional participant's data was omitted from the pupillometric results due to a malfunction by the eye-tracker causing the data to not be recorded. All fixations that occurred after

7200ms were removed, as these dilations would have occurred after the response time limit had already passed.

Reaction time

Using the lme4 package in R, we analysed the effects of trial type, sound type, and target/non-target ratio on reaction time in the AX-CPT auditory task. Building off a null model that only included subject number as a random effect, trial type ($b=-0.11$, $se=0.01$) and an interaction between trial type and sound type ($b=0.09$, $se=0.01$) were the only predictors to show a significant effect ($|t| > 2$). Histograms show that the data follows a normal distribution, centred at mean 0. The results followed the general trend found in Chatham et al.'s experiment. Proactive control causes slower AY trials by forcing an override of the prepared target response, but also leads to faster BX/BY trials as there is more time to prepare the non-target response. AY had the slowest response in both ratio groups, with an overall average response time of 1010.97ms. In contrast, AX averaged 804.24ms, BX averaged 818.79ms, and BY averaged 902.44ms. The interaction between sound type and trial type shows that the animal noise group was noticeably slower for AY (the mean is 1091.7ms for animal noises, 939.66ms for letter names) and BY trials (1025.76ms for animal noises, 793.14ms for letter names) (fig. 1-2). Nonetheless, this still follows the general trend, with AY still the slowest for both sound types. These results suggest that adult participants show proactive control toward auditory stimuli. They also seem to suggest that neither sound type nor ratio group significantly affect reaction time on their own.

Pupil Dilation

We constructed a mixed models linear analysis to examine the effects of trial type, sound type, and ratio group on average percent change of pupil dilation during the task. Again building off a null model with only subject number as the random effect, only trial type ($b=-0.03$, $se=0.001$) and an interaction between trial type and ratio ($b=0.02$, $se=0.001$) proved to be significant predictors of average percent of pupil dilation change ($|t| > 2$). This partially aligns with the reaction time results, as ratio and sound type again do not appear to significantly affect pupil dilation on their own. However, trial type and ratio interact to significantly affect pupil dilation, whereas it was an interaction between trial type and sound type that affected reaction time. As shown in figures 3 and 4, all trial types follow the same trend, with increased change in pupil dilation during the delay and probe periods. There is little variance shown between ratio groups; all significant variance is between trial types

(table 1-2). These results suggest that adult participants show proactive control toward auditory stimuli. They also suggest that sound type does not significantly affect pupil dilation on its own. These results seem to show that ratio group causes significant differences in change of pupil dilation, particularly in AX trials. AX shows the highest percentage of change on average for the 70% non-target group (Fig. 2), whereas it shows the lowest percentage of change for the 70% target group (Fig. 3). This suggests that while AX trials were still faster than AY trials for both ratio groups, ratio does affect mental effort.

DISCUSSION

Our results support our main hypothesis that fully developed cognitive control processes auditory stimuli similarly to how it processes visual stimuli. In Chatham, Frank, and Munakata's experiment, AY trials resulted in longer reaction times than AX, BX, or BY trials for 8 year old participants. This is because developed proactive control responds to a cue hinting at a possible target response (A) by preparing to provide such a response, then must override that preparation upon recognizing the non-target probe (Y). Our experiment produced similar results, with AY trials producing the longest reaction times of all trial types, regardless of ratio or sound type. The pupillometric data proved to be largely similar to that of visual stimuli as well, with increases in pupil dilation occurring during the delay and probe periods for all group types.

Our results support the idea that the type of sound heard does not significantly affect cognitive control. Animal noises and letter names produced similar mean reaction times to one another for both target and non-target trials, and follow the general trends set by previous visual AX-CPT studies like Chatham, Frank, and Munakata's. Pupil dilation also occurs at similar intervals for both sound types. This suggests that human cognition does not differentiate between specific sources of a single type of stimuli. It also helps to disprove type of sound as a possible confounding factor for why cognitive control shows similar processing towards both visual and auditory stimuli.

Our results go against our hypothesis that adjusting the ratio of target to non-target trials can affect whether the stimuli are processed proactively or reactively. Regardless of whether there were more target trials or non-target trials in the current block, participants

showed increases in pupil dilation both during the delay period and after the probe. Contrary to the pattern shown among eight year olds in the previous study, our adult participants showed a far greater increase in dilation after the probe than they did during the delay. Moreover, this pattern remained consistent in all four trial types. However, while ratio did not affect reaction time or the general trend of pupil dilation, it did appear to affect how much the pupils dilated for different trial types. AX had the highest average change in pupil dilation overall for the 70% non-target group, but the lowest overall for the 70% target group. This implies that participants were more focused on target trials when occurred less often and were less focused when they occurred very frequently. This could mean that changing the ratio does actually affect pupil dilation; but rather than adapting by responding either more proactively or reactively during the different periods of the task, participants instead just adapt by lowering their mental effort overall. It appears that fully developed adults manipulate their cognitive control within the structure of proactivity, rather than reverting back to reactivity. Future research should work to see if this is indeed the case.

A potential flaw in this experiment was the small sample size. Resources only allowed for one participant to be tested at a time, resulting in 40 being the most efficient for the testing period allotted. Another issue could be variance in the eye tracking procedure; several subjects either wore glasses or eye makeup which may have affected the eye tracker's accuracy. Unlike in tasks testing visual stimuli, there was nothing on screen for participants to focus on during the experiment. This may have had an unknown effect on tracking pupil dilation.

These findings open up a broad new range of opportunities for research on cognitive control. Experiments that had previous only been done using visual stimuli can now use sounds instead. This would allow researchers to test for cognitive control in groups who have trouble seeing, such as the blind or the elderly. Now that we know the cognitive control mechanism for vision and audition is fundamentally similar, it allows for more comparisons between the two. Future research might test whether an individual can have greater efficiency (in terms of accuracy or reaction time) for sensing one type of stimuli over another. Past studies have only used sound as a distraction to visual cognitive control, but not as another task on it entirely. An interest study might also be to see whether attempting to use cognitive control on both types of stimuli simultaneously causes more degradation on one or the other, suggesting one sense gets priority when under high cognitive load. Our findings also build off of Chatham et al.'s developmental research and allow for future research to attempt to

determine the rate at which cognitive control develops, and if it develops at the same rate between the different senses. While Chatham's study showed that significant development occurs between the ages of 3.5 and 8 years, it only shows it for visual stimuli. Cognitive control towards sounds could develop at a slower or faster pace. For either type of stimuli, the greatest growth period could even occur at an age that has not yet been tested. This experiment should also be repeated to confirm its results with larger sample sizes. A possible variation could mix different types of sound into a trial, such as making the cue animal sounds and the probe letter names. This would make it possible to see if cognitive control is affected when the stimuli are not relevant to one another.

The human mind responds to aural stimuli in a similar manner as it responds to visual stimuli. This is important as it adds more evidence to the theory that cognitive control is domain general. It provides us a better understanding of how the mind works to interpret different aspects of the environment as efficiently as possible. It supports the idea that the senses do not operate as separate mechanisms, but instead all work as different branches from the same neural base.

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Figure

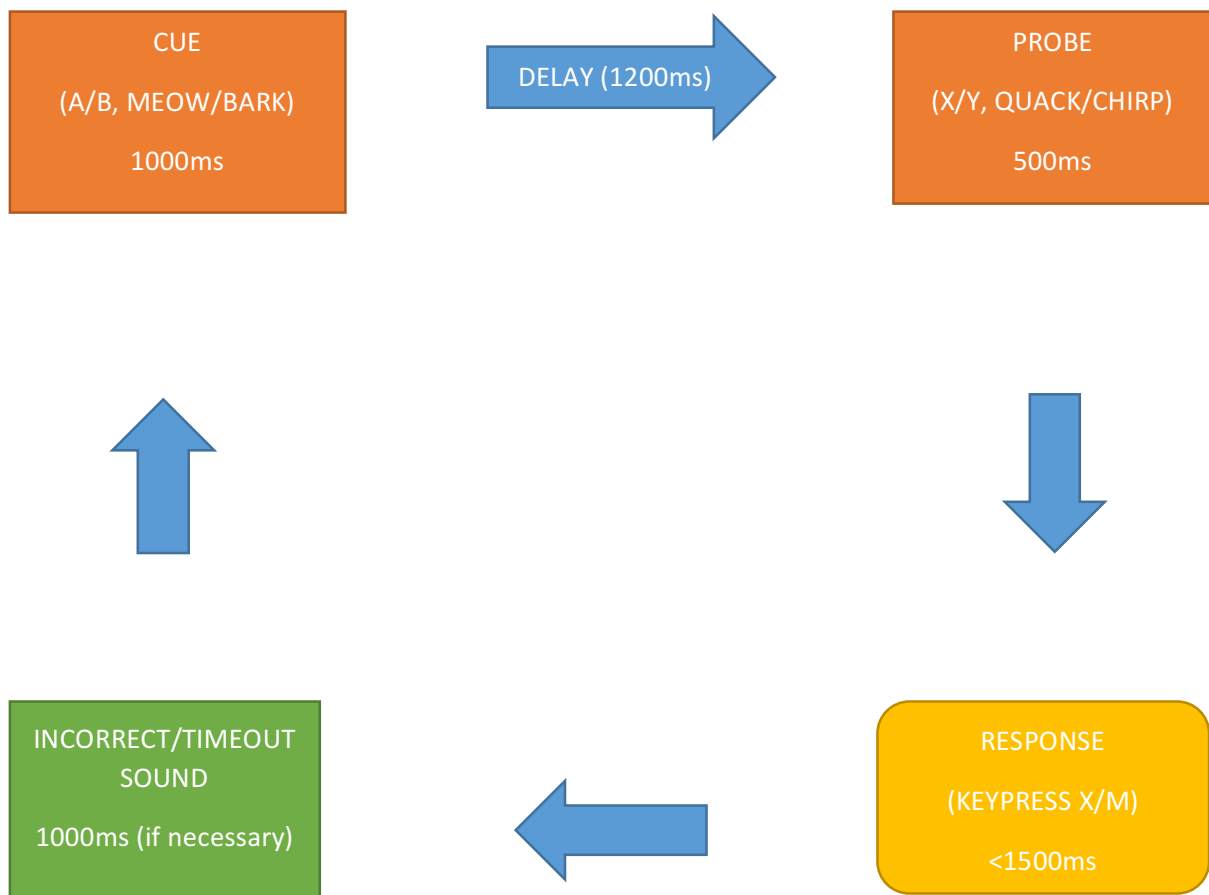


Figure 1: The steps of a single trial. Each trial begins with a cue sound that lasts 1000ms (the actual sound is approximately 500ms). After a delay period of 1200ms, the probe sound starts. Participants are able to respond once the probe sound begins, and so are given a total of 2000ms to provide a keypress response. Once they have either responded or reached the time limit, the trial ends and they start the next trial with another cue sound. If their response was incorrect or after the time limit, a 1000ms alert sound will go off before proceeding to the next trial.

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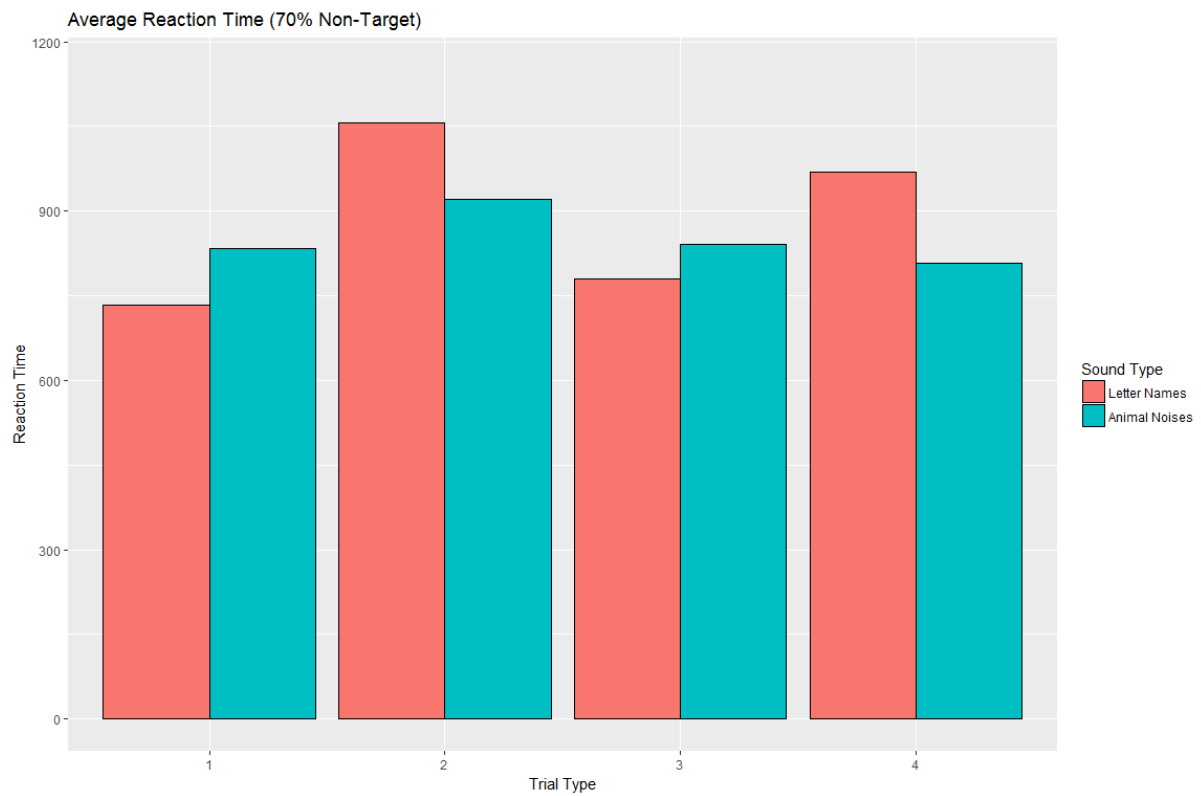


Figure 1: Average reaction time for the 70% non-target/30% target block. AY trials have the longest reaction time for both sound types. Participants who listened to letter names took longer than those who listened to animal noises in AY and BY trials, while animal noises took longer on AX and BX trials.

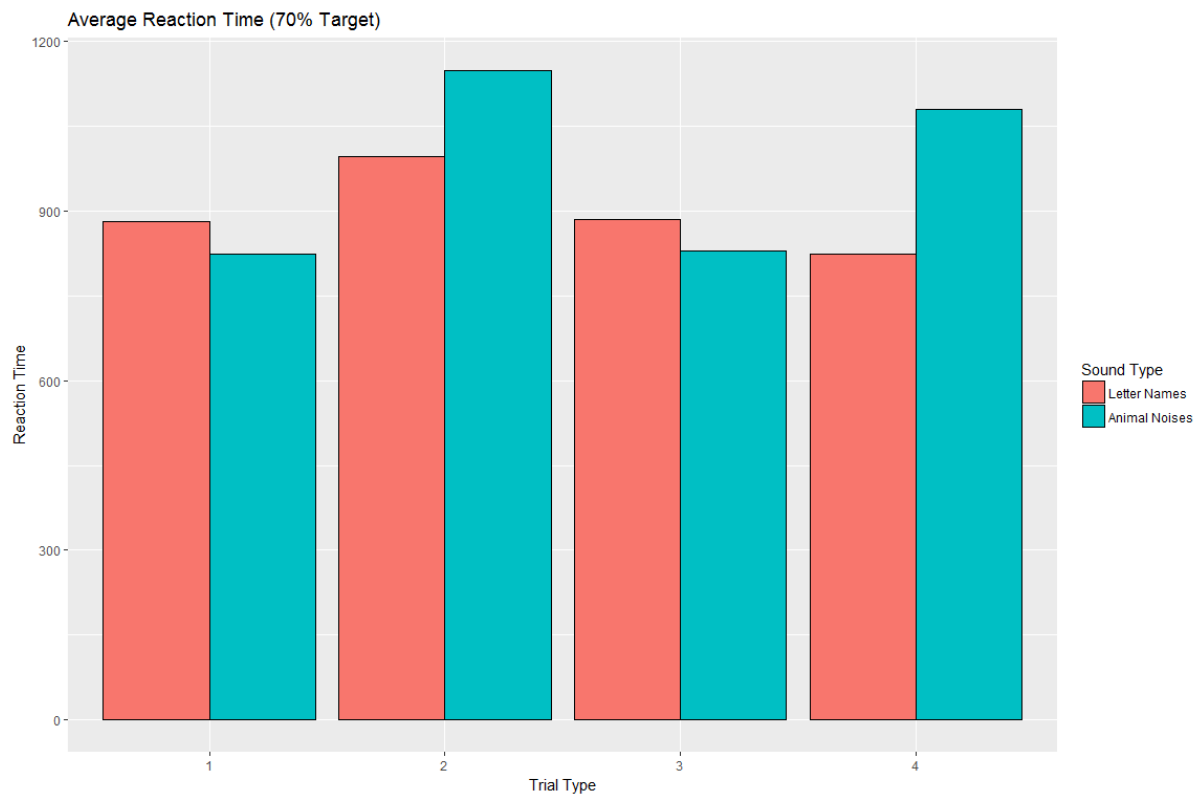


Figure 2: Average reaction time for the 70% target/30% non-target block. AY trials still have the longest reaction time. Participants who listened to animal noises took longer for AY and BY trials than those who listened to letter names. Letter names now take longer on AX and BX trials.

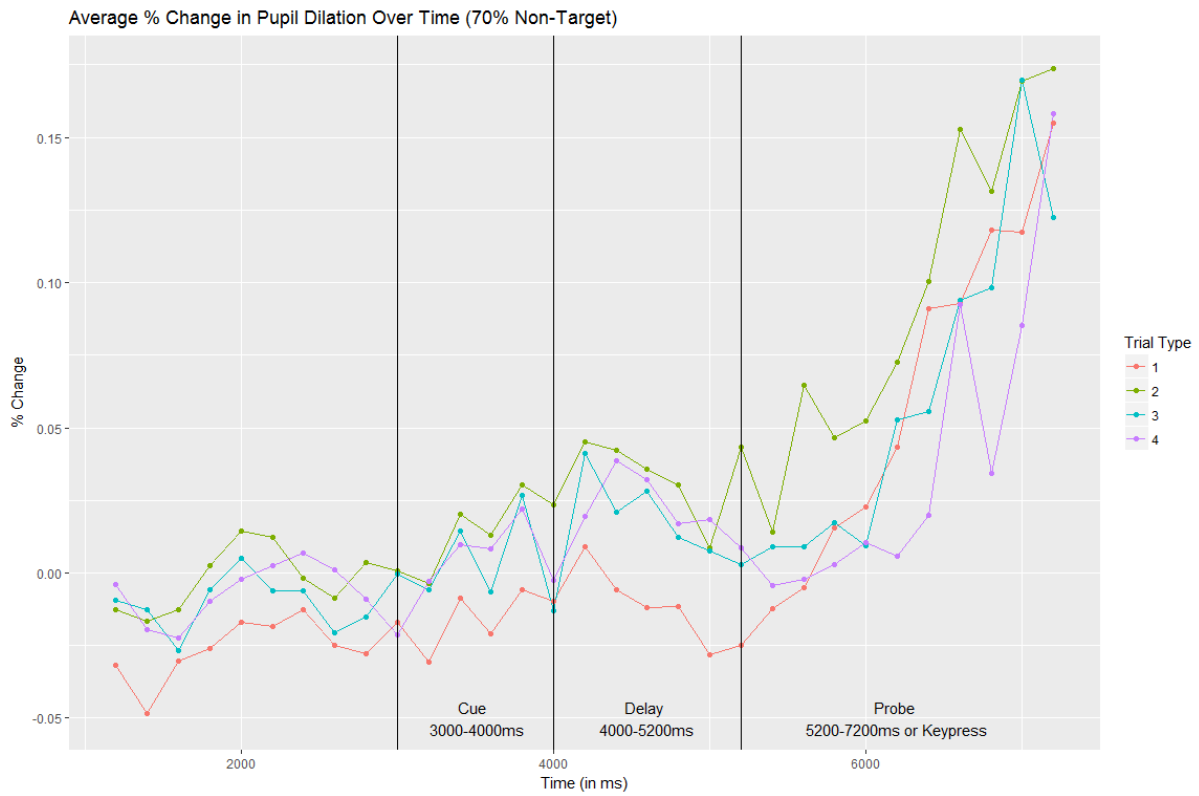


Figure 3: Average percent change in pupil dilation over time for the 70% non-target/ 30% target ratio block. All trial types follow the general trend for proactive control, with increased pupil dilation during the delay period and after the probe. Trial type 1 (AX) shows the least change in pupil dilation before the probe, while trial type 2 (AY) shows the most change throughout.

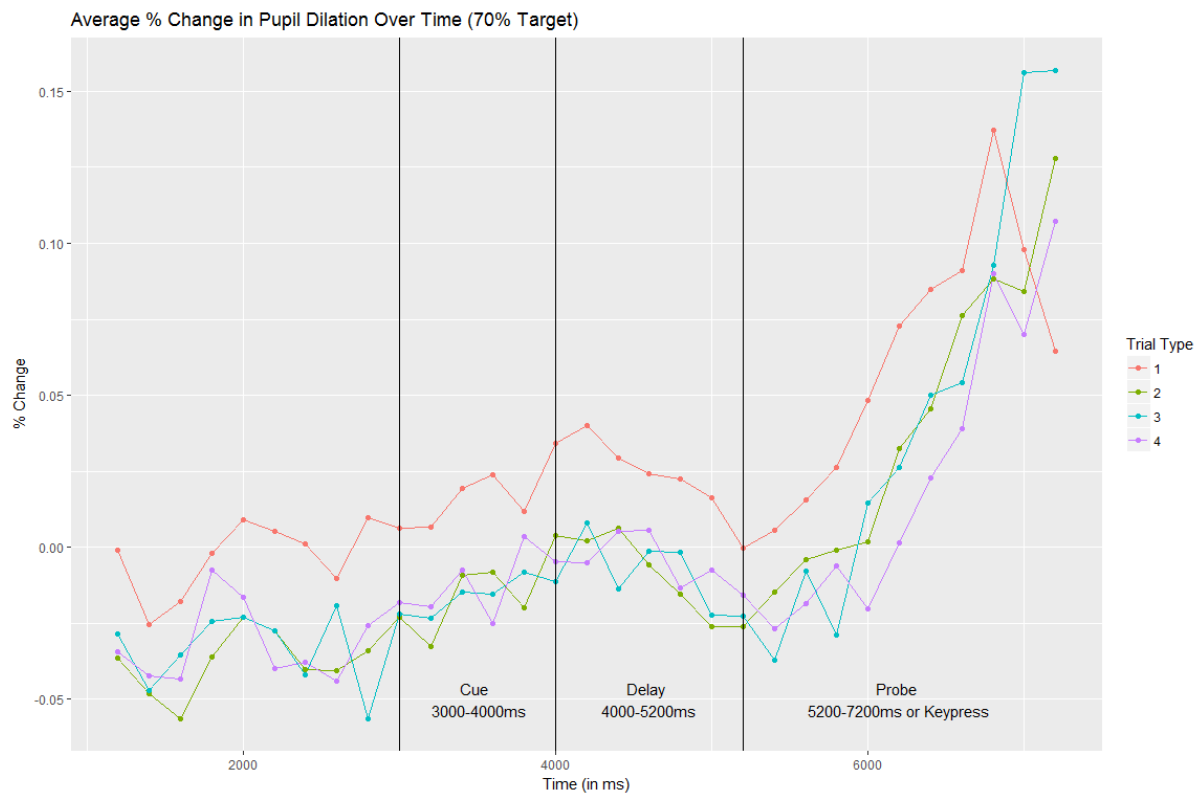


Figure 4: Average percent change in pupil dilation over time for the 70% target/ 30% non-target ratio block. All trial types follow the general trend for proactive control, with increased pupil dilation during the delay period and after the probe. Unlike for the non-target group, trial type 1 (AX) shows the most change on average.

Tables

	Estimate	Std. Error	t value
Trial Type 1 (AX)	0.0147412	0.0009398	15.69
Trial Type 2 (AY)	-0.0301478	0.0017263	-17.46
Trial Type 3 (BX)	-0.0318653	0.0019413	-16.41
Trial Type 4 (BY)	-0.0299763	0.0019309	-15.52

Table 1: Fixed effects of average percent change in pupil dilation as predicted by trial type for the non-target 70%/target 30% ratio block. All trial types significantly differ in how they affect pupil dilation.

	Estimate	Std. Error	t value
Trial Type 1 (AX)	0.013125	0.001099	-11.940
Trial Type 2 (AY)	0.034174	0.001942	17.594
Trial Type 3 (BX)	0.018558	0.002154	8.615
Trial Type 4 (BY)	0.018518	0.002123	8.723

Table 2: Fixed effects of average percent change in pupil dilation as predicted by trial type for the target 70%/non-target 30% ratio block. All trial types significantly differ in how they affect pupil dilation.